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Environmental aspects of ethanol-based fuels from *Brassica carinata*: A case study of second generation ethanol

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ABSTRACT

One of the main challenges faced by mankind in the 21st century is to meet the increasing demand for energy requirements by means of a more sustainable energy supply. In countries that are net fossil fuel importers, expectation about the benefit of using alternative fuels on reducing oil imports is the primary driving force behind efforts to promote its production and use. Spain is scarce in domestic energy sources and more than 50% of the energy used is fossil fuel based. The promotion of renewable energies use is one of the principal vectors in the Spanish energy policy. Selected herbaceous crops such as *Brassica carinata* are currently under study as potential energy sources. Its biomass can be considered as potential feedstock to ethanol conversion by an enzymatic process due to the characteristics of its composition, rich in cellulose and hemicellulose. This paper aims to analyse the environmental performance of two ethanol-based fuel applications (E10 and E85) in a passenger car (E10 fuel: a mixture of 10% ethanol and 90% gasoline by volume; E85 fuel: a mixture of 85% ethanol and 15% gasoline by volume) as well as their comparison with conventional gasoline as transport fuel. Two types of functional units are applied in this study: ethanol production oriented and travelling distance oriented functional units in order to reflect the availability or not of ethanol supply. E85 seems to be the best alternative when ethanol production based functional unit is considered in terms of greenhouse gas (GHG) emissions and E10 in terms of non-renewable energy resources use. Nevertheless, E85 offers the best environmental performance when travelling distance oriented functional unit is assumed in both impacts. In both functional unit perspectives, the use of ethanol-based fuels reduces the global warming and fossil fuels consumption. However, the contributions to other impact indicators (e.g. acidification, eutrophication and photochemical oxidants formation) were lower for conventional gasoline.

Life Cycle Assessment (LCA) procedure helps to identify the key areas in the *B. carinata* ethanol production life cycle where the researchers and technicians need to work to improve the environmental performance. Technological development could help in lowering both the environmental impact and the prices of the ethanol fuels.

Contents

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1. Introduction

One of the main challenges faced by mankind in the 21st century is to meet the increasing demand for energy requirements by means of a more sustainable energy supply. The current energy supply is unsustainable due to its strong dependence on fossil fuels (natural gas, oil and coal). The combustion of fossil fuels is the largest contributor to the growing concentration of greenhouse gases (GHG) in the atmosphere [1].

In countries that are net fossil fuel importers, expectation about the benefit of using alternatives fuels on reducing oil imports is the primary driving force behind efforts to promote its use and production, since they could improve the security of energy supply. In addition, alternative fuels would help in reducing the GHG and other pollutant emissions as well as could support development on rural areas [2].

Around 40% of the total energy consumption in the world is in form of liquid fuels such as gasoline or diesel [3]. Hence, special attention has been paid to biofuels, which are predominantly in liquid forms.

In Spain, approximately half of the energy used is oil based. Spain is scarce in domestic energy sources and only coal is produced nationally in large amounts. Only 5.9% of total Spanish primary energy requirements as well as 16.6% of the total electricity production comes from renewable sources [4]. The promotion of renewable energy use is one of the main vectors in the Spanish energy policy, which is materialized in the existence of specific objectives for each technology [5].

Among biofuels, ethanol is the one that is attracting most attention since it is produced in large amounts in Europe and has the potential of being a sustainable transportation fuel as an alternative to gasoline [6,7]. In fact, it is used in the light duty vehicle fleet in a large number of countries [8,9]. However, concerns have been raised about the ecological, economical and social impacts of ethanol production and to which extent the total sum of these impacts undermines a sustainable development and use of this energy source [10].

The European Union is the fourth producer of ethanol in the world behind the United States, Brazil and China, with an annual production of 1770 million litres in 2007, which represents an increase of 13% compared to 2006. Spain is the third producer of ethanol in Europe (behind France and Germany) and about 348 million litres of ethanol were produced in 2007. Cereals like barley and wheat are currently the most common crops for ethanol production [11]. However, the current focus on ethanol production is the conversion of non-edible sources (known as second generation ethanol) such as lignocellulosic biomass, which is made up mainly of cellulose, hemicellulose and lignin [3,12]. Potential feedstocks include materials such as herbaceous crops and agricultural and forest residues. The abundance and low cost of this kind of materials make them attractive as feedstock.

Selected herbaceous crops such as *Brassica carinata* are currently under study as potential energy sources. This crop is a source of non-food biomass to be processed into energy (heat and power). However, other products can be obtained from *B. carinata*. For example, oil from its seeds can be extracted in order to produce biodiesel and other high added value products [13,14]. This biomass could be considered as a potential alternative to ethanol conversion by an enzymatic process due to the characteristics of its composition. About 33% of *B. carinata* dry matter consists of cellulose and 22% is hemicellulose, which are the potential feedstocks for producing ethanol.

Life Cycle Assessment (LCA) methodology has proved to be a valuable tool for analysing environmental considerations of product and service systems that need to be part of decision making process towards sustainability [15]. Several publications are already available on LCA studies carried out to identify the environmental performance of the production of ethanol from different cellulosic feedstocks and the subsequent use of the fuel in vehicles [7,8,16–19] and several differences have been found in the results specifically due to the lack of a commercial cellulosic ethanol production line [7].

So far, no LCA study has been carried out to assess the environmental impacts of cellulosic ethanol from *B. carinata* biomass. This paper focuses on ethanol from *B. carinata* involving the cellulosic technology and the environmental performance analysis of using ethanol blends in a middle sized, recent car. Blends of ethanol as 10% and 85% in volume with gasoline (E10 and E85, respectively) will be the goal of the study and their comparison with conventional gasoline (CG).

There are different ways of defining the functional unit (FU) and the influence of its choice on the results is particularly important when the results of the LCA are indicated to be used as a decision support tool. In addition, choice of the FU is highly dependent on the aim of the study. Two types of functional units will be handled in this study and all of them satisfy the function of this study: ethanol production based FU (kg ethanol) and travelling distance based FU (km driven). Nowadays, biofuels are commercially uncompetitive with fossil fuels in Europe and also in Spain, the technology is under development and although lignocellulosic biomass is abundant and does not compete with the production of food crops, not all cellulose biomass is suitable and can be used as feedstock due to the constraints of present technology to hydrolyze the biomass efficiently in terms of cost and energy consumption [3]. In addition, dedicated energy crops are considerably more expensive than agricultural and forest residues (up to 50% more per ton) and only are attractive alternatives if they are properly integrated into existing agricultural activities and complement the current cropping options [6,20]. The annual volume of gasoline consumed in the transport sector in Spain was around 6700 Mkg in 2007 [21]. If ethanol-based fuels substitute all the gasoline used in transport sector, the use of E10 and E85 should require 710 Mkg and 7810 Mkg of ethanol pure, respectively. However, the production of ethanol in Spain was around 268 Mkg in 2007 [11], which show that the actual Spanish capacity of ethanol production is not enough and not available in markets to satisfy all the gasoline requirements. In this context, the functional unit based on ethanol production should be more relevant to the present situation.

Given the constraints of ethanol production from the current available technologies and feedstocks, Europe is putting a considerable attempt in second generation biofuels, derived from cellulosic materials. The conversion of lignocellulosic material to ethanol has received special attention in Sweden and to a minor extent in UK, Spain and the Netherlands [22]. Cellulosic ethanol (produced from wood, grasses, or the non-edible parts of plants) is expected to be available in the markets in a future. In this case, the

travelling distance based FU should be more relevant to analyse the environmental profiles of both blends.

The environmental profile is addressed in terms of fossil fuel extraction (crude oil, natural gas and coal), global warming, acidification, eutrophication and photochemical oxidants formation. The full life cycles of ethanol and gasoline are analysed from a cradle to grave perspective in both functional units under study, including the production and transport of raw materials and fuels, the production of equipments and energy in the plant, and the application of fuels.

2. Methodology

Life Cycle Assessment (LCA) is a method for determining the environmental impact of a product (good or service) during its entire life cycle, from extraction of raw materials through manufacturing, distribution and use to final use and disposal [23]. Nevertheless, LCA as it stands has its limitations such as the difficulties in data acquisition and validation. Allocation issues can also become a limiting factor in some cases due to the ambiguous results that can be obtained when using different methodologies.

In this study, LCA was used to compare the environmental performance of internal combustion engine vehicles fuelled with blends of gasoline and ethanol (E10, E85) and conventional gasoline (CG), without local circumstances playing a role. Regarding the impact assessment stage, CML 1999 baseline impact assessment factors were chosen and modelling was performed using CMLCA (Chain Management by Life Cycle Assessment) [24].

2.1. Goal and scope definition

The objective of this study is to identify and compare the environmental impacts of ethanol applications (E10 and E85) with CG in an average car in Spain, resulting from two different functional units. The scope of the study includes the life cycle of ethanol use from a cradle to grave perspective, including *B. carinata* cultivation, ethanol conversion and transport to a blending refinery, blending of ethanol with gasoline and storage and finally the combustion of fuel in an average car in both functional units.

2.2. Functional unit

The functional unit provides the reference to which all inputs and outputs of the product system are related [23]. There are different ways of defining the functional unit and the influence of its choice on the results is particularly important when the results of the LCA are indicated to be used as a decision support tool. Two types of functional units are defined in this study and in both, the whole life cycle of the ethanol blends was taken into account:

(a) An ethanol production based functional unit is important when ethanol supply is limited. It was defined as 1 kg of pure ethanol.
(b) A travelling distance based functional unit is important when ethanol supply is not limited. It was defined as 1 km driven by an ethanol-based fuelled vehicle.

2.3. System boundaries

The system boundaries include *B. carinata* cultivation, transport of biomass to an ethanol plant, ethanol conversion, transport and distribution of ethanol, and ethanol fuelled vehicle use. The conventional gasoline fuelled vehicle use is included within the system boundaries in order to compare the environmental impact results between ethanol-based fuels use. Fig. 1 describes the system boundaries of the system under study.

1) *B. carinata* culture: a standard hectare plot was selected out of all the 160 ha cultivated in Soria (Spain). The climate conditions in the region analysed are continental-Mediterranean. The mean annual temperature is 10.5 °C and annual rainfall is about 500 mm. The texture of the soil was sandy loam: sand 5–9%, organic matter 22–23% and clay 68–73%. Oxidizing organic matter was about 1% and pH around 6. The soil is light with good drainage.

   The production of the different consumable inputs such as fertilizers (N, P, K), pesticides and seeds were considered within the system boundaries as well as their transport from wholesalers to farm gate. Diffuse emissions from fertilizer application and emissions from agricultural machinery (fertilizing, tillage, sowing, harvesting and transport) have also been taken into account. The binding of CO_2 from the atmosphere was taken into account and estimated by the C-content in the dry matter multiplied by the stoichiometric factor 44/12, based on the assumption that the carbon in the biomass is completely taken from the air (~1.74 kg CO_2/kg biomass). The farmers transport to carry out and supervise the crop was also included.
2) Ethanol conversion plant: biological conversion of lignocellulosic feedstocks to ethanol is the process receiving the most attention, therefore, being the process considered in this study [7]. The ethanol production material and energy balances as well as ethanol yield are based on the ethanol conversion technology reported by the National Renewable Energy Laboratory [25] from corn stover, assuming that ethanol production efficiency is equal for other crops. In this case, feedstock composition was adapted to *B. carinata* composition (Table 1). In the ethanol conversion process, cellulose and hemicellulose are used for ethanol production. The lignin fraction of the biomass (roughly 19% of total dry matter) has a high heating value and is used as fuel in a lignin combustor in order to produce the energy requirements for the plant. The ethanol conversion procedure was divided in nine processes (Fig. 1): (i) feedstock handling and storage; (ii) pre-treatment and conditioning; (iii) saccharification (or enzymatic hydrolysis) and co-fermentation; (iv) distillation and dehydration to purify and concentrate the ethanol up to 99.5%; (v) storage of ethanol; (vi) wastewater treatment plant (WWTP); (vii) energy production (electricity and heat process) from solids from distillation, syrup and biogas, (viii) enzyme production (all enzymes needed in the process are produced in the own plant) and (iv) ancillary utilities, which include the production of cooling, sterile and process water as well as the compressed air. Solid wastes produced such as gypsum and ashes are sent to landfill and their transport was included in the system boundaries.
3) Ethanol–gasoline blending refinery: gasoline production and transport up to petrol stations as well as the blending step of

Table 1
Composition of *Brassica carinata* biomass used as lignocellulosic feedstock (data obtained from Ballesteros et al. [13]).

Component	Dry matter (%)
Cellulose	32.7
Hemicellulose	21.9
Xylan	18.0
Arabinan	1.2
Other sugar polymers	2.7
Lignin	18.7
Ash	5.2
Extractives	20.9
Total	100.0

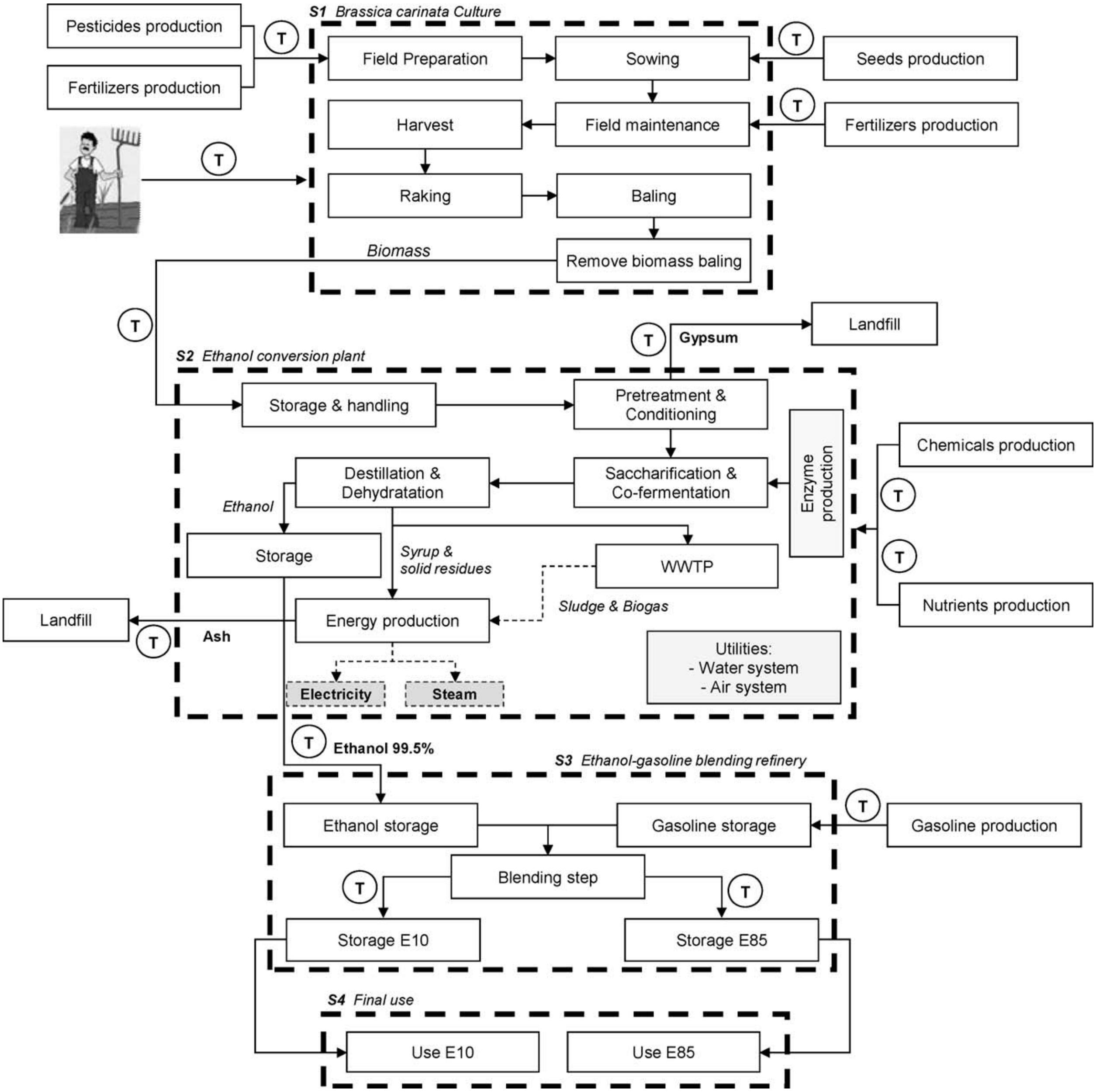

Fig. 1. Life cycle of ethanol from *Brassica carinata* biomass (T, transport).

gasoline and ethanol to produce the ethanol-based fuels under study (E10 and E85), and their regional storage have been considered in this subsystem.

4) Final use: the combustion of fuels described before in an average passenger car was evaluated and emissions were calculated according to the amount of ethanol and gasoline necessary to drive the equivalent distance according to the functional unit under study. Important factors in this study are the fuel economy of the vehicle and the air emissions associated with operating the vehicle. Information regarding specific gravity and energy density properties of gasoline and ethanol necessary to estimate the efficiency of the engine with E10, E85 or gasoline as fuels were taken from [18]. The combined fuel economy assumed of E10 and E85 fuelled vehicles was 14.5 km/kg and 10.9 km/kg, respectively. The environmental burdens associated with the vehicle production system and vehicle maintenance are not included in the analysis.

2.4. Inventory analysis

The most effort consuming step of the execution of LCA studies is the collection of inventory data in order to build the life cycle inventory (LCI). Moreover, high quality data is essential to make a reliable evaluation. Data used in this study was collected from different sources and in many different ways.

Background information from *B. carinata* cultivation (S1) was obtained from field data during the establishment of 160 ha in Soria (Spain) in 2003 [26]. Transportation of consumable inputs to the farm, such as fertilizers and herbicides, is included within the subsystem boundary and an average transport distance of 500 km was assumed per lorry. Each lorry transported a total of 32 tonnes. Data related to the production of agrochemicals was taken from [27]. Application of nitrogen-based fertilizers results in emissions of N_2O, NO_x, NH_3 and nutrient leaching. All of them were calculated using emission factors proposed by [28,29]. Diffuse emissions from herbicide use were calculated according to the method proposed

Table 2
Assumptions about transport activities related to ethanol-based fuels production.

Materials	Transport mode	Capacity	Average distance
Biomass bales from farm to refinery gate	Diesel lorry	16 tonnes	25 km
Chemicals from wholesalers to plant gate	Diesel lorry	16 tonnes	50 km
Solid wastes from plant to landfill gate	Diesel lorry	16 tonnes	20 km
Ethanol from plant to blending refinery gate	Diesel lorry	32 tonnes	20 km
E10 and E85 blends to regional storage	Diesel lorry	32 tonnes	34 km

by Hauschild [30]. Average transport distance for biomass bales up to the ethanol plant was assumed to be 25 km (Table 2). The next step was the conversion of the *B. carinata* biomass to ethanol (S2). This method involves an enzymatic hydrolysis process followed by fermentation and distillation. The conversion process was modelled in this study for a biomass capacity treatment of 98,958 kg/h and the ethanol production mass and energy balances necessary to carry out the LCA were based on the conversion technology developed by the National Renewable Energy Laboratory [25] and were adapted to the composition of *B. carinata*. This technology was selected because of its precision on presentation of the inventory data. Emissions from the production of capital goods were taken from the EIPRO database [31] and inventory data for production of chemicals was taken from Althaus et al. [32]. It was assumed that the transport of chemicals was carried out by lorries of 16 tonnes. The transport distance was assumed to be 25 km. Moreover, the solid wastes generated in the ethanol plant such as ashes and gypsum were sent to landfills and 25 km were assumed as delivery distance by means of 16 tonnes lorries. Inventory data for the landfill process was taken from Doka [33]. All the enzyme requirements in the ethanol plant were believed to be produced in the own plant and inventory data were taken from Wooley et al. [34].

The ethanol conversion plant uses renewable resources such as the lignin fraction of the biomass, biogas and sludge from the wastewater treatment plant (WWTP) and other solid wastes as fuel. There is no fossil fuel consumption to satisfy the energy requirements as well as electricity consumption from the grid. Thus, the ethanol conversion plant modelled here is energy self-sufficient (steam and electricity) and there is no electricity surplus to send to the national grid. The recovered water from the WWTP is sent back to the process as recycled water. A short description of the inventory data is shown in Table 3.

Blending ethanol into gasoline to produce E10 and E85 (10% and 85% by volume of ethanol added to gasoline) was assumed in the S3 as well as fuel distribution to regional storage (34 km by 32 tonnes lorries). Inventory data for the gasoline production and distribution to the blending refinery was taken from Spielmann et al. [35]. Information regarding specific gravity and energy density properties of pure gasoline and ethanol necessary to estimate the efficiency of the engine running on E10, E85 and CG was taken from Sheehan et al. [18]. Emissions from E10 and E85 combustion (S4) are based on a standard test procedure, covering a mix of driving on urban roads and on motorways. This data was taken from published reports [36,37].

2.5. Allocation procedure

Allocation is one of the most critical issues in LCA methodology. This is required for multi-output processes and the selection of an allocation approach for processes that produce more than one co-product can have a strong effect on the results. In this study, allocation procedure was not needed because *B. carinata* biomass crop yield only biomass, not seeds. Concerning the ethanol plant, allocation was also avoided because of all electricity produced

Table 3
Global inventory for *Brassica carinata*-based ethanol production.

Inputs from the technosphere

Materials	Value	Energy	Value
Brassica carinata biomass (20% moisture)	98,958 kg	Electricity[a]	29,534 kWh
Vinyl acetate	23,8 kg	Steam[a]	523,000 MJ
Sulphuric acid	2,958 kg		
Lime	2,156 kg	**Transport**	**Value**
Diammonium phosphate	22 kg	16 tonnes lorry	2,834 tonnes km
Corn steep liquor	175 kg		
Enzyme	5,702 kg		
Nutrient feed	53 kg		

Inputs from the environment

Materials	Value
Well water	179.5 m^3

Outputs to the technosphere		Outputs to the environment	
Materials	Value	Emissions to air	Value
Ethanol (99.5%)	19,733 kg	Vapour	218.60 tonnes
		Carbon dioxide	84.51 tonnes
Wastes to treatment		Acetic acid	114.2 kg
Gypsum (to landfill)	3,370 kg	Ethanol	15.17 kg
Ash (to landfill)	1,028 kg	Sulphuric acid	2.00 kg
		Others	203.90 kg

[a] From energy production process from solid wastes and biogas.

from wastes is consumed in the ethanol conversion and enzyme production processes. Thus, there is no surplus of electricity. Solid residues generated in the plant such as gypsum from distillation and ashes from boilers are sent to landfill and were considered as wastes. As a result, all the environmental burdens of the S2 were allocated to the cellulosic ethanol.

3. Environmental impact assessment

Life Cycle Impact Assessment was conducted using characterization factors from CML baseline 1999 methodology [38]. The following parameters have been considered in the analysis: acidification (A), eutrophication (E), photochemical oxidants formation (PO), global warming (GW) and fossil fuels extraction (FF). Special attention has been paid on the GHG emissions and fossil fuels use in order to satisfy the two challenges for the EU in terms of transportation fuels [39]: (i) the reduction of GHG emissions and (ii) improving the security of energy supply.

3.1. Ethanol production oriented functional unit perspective

Table 4 summarizes the LCA characterization results for E10 and E85 when ethanol production oriented functional unit is considered as base of our calculations. One kg of ethanol is able to drive an E10 fuelled vehicle 143 km and E85 fuelled vehicle 13 km. The environmental burdens associated with equivalent distances driven by gasoline fuelled vehicle were subtracted from those of the ethanol production system. Changes in the results represent

Table 4
Potential environmental impacts based on ethanol production oriented functional unit perspective (1 kg ethanol).

Category	Unit	E10	E85
Global warming (GW)	kg CO_2 equiv./FU	−4.43	−4.84
Photochemical oxidants formation (PO)	g C_2H_4 equiv./FU	0.858	1.26
Acidification (A)	g SO_2 equiv./FU	13.59	2.63
Eutrophication (E)	g PO_4^{3-} equiv./FU	3.86	0.897

Table 5
GHG emissions from a passenger car based on ethanol production oriented functional unit perspective (1 kg ethanol).

GHG emission	Unit	E10	E85
CO_2	kg CO_2 equiv./FU	−4.72	−5.15
CH_4	kg CO_2 equiv./FU	−0.040	−0.022
N_2O	kg CO_2 equiv./FU	0.317	0.330

impacts of increasing the share of ethanol in the blend used as fuel as well as differences on fuel economy.

Using E85 seems to be more advantageous than E10 in terms of GHG emissions. If it is analysed in detail the contributions to the GW, the emissions are due mostly to three global warming gases: CO_2, N_2O and CH_4 (Table 5). Here it is necessary to mention the positive effect of the carbon sequestered during the biomass growing which offsets the GHG emissions. Results show that in E85 fuel application, the most important contribution to CO_2 equivalent emissions is the CO_2 taken up during the biomass growing which gets offset CO_2 derived from agricultural machinery emissions, ethanol conversion plant and blend use. When E10 is used, the lowest amount of ethanol in the blend supposes a lower contribution from CO_2 taken up, which cannot compensate CO_2 emissions principally from blend use and fossil fuel production. However, in both cases the CO_2 equivalent emissions are lower than when the same distance is driven with CG (Table 4).

Regarding the use of fossil fuels, 1 kg of ethanol could save 0.57 kg of gasoline in E10 fuel application and 0.67 kg of gasoline in the E85 fuel application. In terms of fossil fuels extraction, coal, natural gas and crude oil have been analysed and results are shown (in kg coal equivalent) in Table 6. It can easily be seen that crude oil contributes largely to the fossil fuel extraction, followed by natural gas and coal, respectively. One kg of ethanol could save 27.9 kg and 30.3 kg of crude oil (in kg coal equiv.) in E10 and E85 fuels use, respectively. However, E85 application would increase the extraction of coal. Although shifting from CG to ethanol blends supposes the consumption of more liquid fuel by the agricultural machineries (usually diesel), less gasoline is necessary to propel the car and hence, the reduction up to 59% and 63% of total fossil fuels consumption when E10 and E85 are used, respectively. The processes contributing most to FF in the life cycle of fuels under study are the agricultural activities (such as fertilising, sowing and chiselling) and the production of lime required in ethanol conversion plant (high requirement of coal).

When other environmental impact potentials (A, E and PO) were analysed, the results are entirely different for both fuels. The results show the increase of contributions to A, E and PO when shifting from gasoline to ethanol fuels since all these impact categories are affected considerably by agricultural activities [17] due to SO_2 emissions from P-based fertilizer manufacture, N-based emissions from N-based fertilizer application and NO_x, CO and VOC emissions from diesel combustion in agricultural machinery. In this study, E85 has better environmental profile in A and E than E10 use, and E10 fuel application shows better environmental performance than E85 in terms of PO. The higher fuel economy of an E10 fuelled car compared to an E85 fuelled car, as well as the higher proportion of ethanol in the blend, are the main responsible of PO, A and E contributions.

Table 6
Savings of fossil fuels extraction (kg coal equivalent/FU) in comparison with CG on ethanol production oriented functional unit perspective (1 kg ethanol).

Fossil fuels	E10	E85
Coal	−0.053	0.002
Natural gas	−1.23	−1.04
Crude oil	−27.9	−30.3
Total	−29.2	−31.3

Table 7
Potential environmental impacts based on travelling distance oriented functional unit perspective (1 km driven distance).

Category	Unit	E10	E85
Global warming (GW)	kg CO_2 equiv./FU	−31.0	−372
Photochemical oxidants formation (PO)	g C_2H_4 equiv./FU	0.006	0.097
Acidification (A)	g SO_2 equiv./FU	0.095	0.202
Eutrophication (E)	g PO_4^{3-} equiv./FU	0.027	0.069

3.2. Travelling distance oriented functional unit perspective

Table 7 summarizes the LCA characterization results for E10 and E85 when travelling distance based functional unit is considered as a base for our calculations. Once more, the environmental burdens associated with the distance driven by gasoline fuelled vehicle were subtracted from those of the ethanol production system. One km driven with E10 fuel requires 7 g of ethanol and 62 g of gasoline, 1 km driven with E85 needs 78 g of ethanol and 14 g of gasoline and, 1 km driven with CG needs 66 g of gasoline.

The results show that using ethanol blends in form of E10 and E85 as a gasoline substitute leads to a reduction of GHG emissions. However, for PO, A and E, CG offers better environmental performance than using ethanol blends. The adverse effects are mainly due to the environmental burdens related to agricultural activities.

When replacing gasoline by ethanol fuels, emissions causing PO, A and E from gasoline production decrease, but emissions from ethanol and biomass production increase. Acidification is originated mainly from SO_2 emissions from the P-based fertilizer production and combustion emissions (e.g. NO_x) from diesel used in agricultural machinery and ethanol-based fuel use. These combustion emissions contribute also to eutrophication as well as other N emissions derived from fertilizer production and use. Diesel combustion in agricultural machinery and ethanol fuel use present a high contribution to PO because of the emissions of CO and NMVOC. Table 8 summarizes air emissions from the life cycle of each fuel.

The contributions of crude oil, natural gas and coal to FF are summarized in Table 9. It can undoubtedly be seen that crude oil contributes largely to the fossil fuel extraction, followed by natural gas. Once more, using E85 fuel presents a better environmental performance than E10 in terms of non-renewable energy resources

Table 8
Air emissions from the life cycle of each fuel based on travelling distance oriented functional unit perspective (1 km driven distance).

Fuel	CO (mg/km)	NMVOC (mg/km)	NO_x (mg/km)	NH_3 mg/km)	SO_x (mg/km)	N_2O (mg/km)	CO_2 (kg/km)
CG	1560	83.9	561	0.640	383	0.712	0.251
E10	1500	84.9	735	14.5	371	8.19	0.218
E85	1900	98.5	675	161	297	86.6	−0.145

Table 9
Savings of fossil fuels extraction (g coal equivalent/FU) in comparison with CG use on travelling distance oriented functional unit perspective (1 km driven distance).

Fossil fuels	E10	E85
Coal	−0.37	0.15
Natural gas	−8.58	−80.2
Crude oil	−195	−2331
Total	−204	−2411

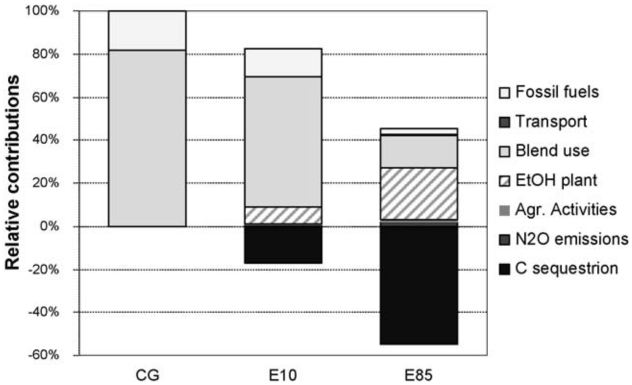

Fig. 2. Contributions of main processes to GW based on travelling distance oriented functional unit perspective. Acronyms: CG, conventional gasoline; E10, mixture of 10% ethanol and 90% gasoline; E85, mixture of 85% ethanol and 15% gasoline.

Table 10
GHG emissions from a passenger car based on travelling distance oriented functional unit perspective (1 km driven distance).

GHG emission	Unit	CG	E10	E85
CO_2	kg CO_2 equiv/FU	0.251	0.218	−0.145
CH_4	g CO_2 equiv/FU	3.65	3.37	1.96
N_2O	g CO_2 equiv/FU	0.211	2.43	25.6

used. Therefore, crude oil consumption could be reduced up to 64% thanks to a lower proportion of gasoline in the blend.

A breakdown of contributions to GW is performed in Fig. 2. This figure indicates that agricultural activities related to *B. carinata* biomass production and ethanol conversion related activities have a noticeable effect over the kg of CO_2 equivalents.

According to our results, gasoline production (included in 'fossil fuels') and use are the main hot spots in terms of GW for CG, roughly 18% and 82%, respectively. Concerning E10, ethanol-based fuel use is the main hot spot followed by gasoline production (90% in volume of the blend). The ethanol conversion stage (specifically, electricity production process) presents a short contribution ($\sim$12%). Nevertheless, the contribution of the fossil fuels production does not decrease in a high proportion, because diesel consumption is increased due to the increase of the agricultural activities. The reason for the decrease in GHG emissions is that the growth of the biomass takes up a large amount of CO_2, counteracted only partly by N_2O-emissions from agriculture. The effect of the increase in the fraction of ethanol in the blends is clearly observed between scenarios E10 and E85: higher amounts of CO_2 are taken up and could get to offset the emissions derived from ethanol production and blend use (Fig. 2).

Regarding GHG emissions shown in Table 10, they are mainly due to emission and uptake of CO_2, emission of nitrous oxide N_2O (from N-based fertilizer application) and of CH_4 (from fossil fuels production). Due to the lower level of crude oil extraction, less CO_2 is emitted from gasoline production when shifting from gasoline to ethanol. However, most of the CO_2 taken up by agriculture production takes place as well as larger amounts of CO_2 are emitted from ethanol production. N_2O emissions increase significantly when ethanol is involved in the fuel cycle because in the agricultural production a large amount of these emissions are released to the atmosphere due to the application of N-based fertilizers. The level of CH_4 emissions decreases lightly.

4. Discussion

The way the input and output data for a LCA are modelled can greatly affect the results. In this study, special attention was paid on the way the functional unit was chosen when the environmental performance of two ethanol–gasoline blends is compared. The functional unit is the central core of any LCA and is the reference unit that forms the basis for comparisons between different systems. Results from both types of functional units considered in this study (ethanol production based and travelling distance based) are slightly different from each other in most of the environmental impact categories.

An overview of several used functional units in other LCA studies has been carried out. In most of the articles investigated the functional unit was based on mass such as kg of ethanol [40,41], on volume e.g. litre of ethanol [7,12,42–44] or on driven distance e.g. km [16,41,45,46] and according to their results, the selection of the functional unit considerably affects the final conclusions. In all cases, shifting from gasoline to ethanol presents environmental advantages in terms of GHG emissions and use of non-renewable energy sources and, environmental disadvantages in terms of A, E and PO emissions. However, environmental advantages of using E10 instead of E85 could present opposite directions. According to Kim and Dale [41], the environmental performance of E10 fuel application is a little better than E85 when mass based functional unit is considered in terms of GW and FF due to E10 fuelled cars move farther than when E85 is used. On the contrary, A and E are slightly worse in E10 due to higher NO_x emissions by ethanol-based fuels. When the volume based functional unit is considered, using E85 results on less GW, FF and PO although, more A and E due to the highest contribution of feedstock production [44]. Finally, considering as a functional unit the power to drive an average passenger car for 1 km (i.e. km), E85 fuel application offers better environmental performance in GW and FF than E10 and less environmental credits in terms of A, E and PO [16,41]. This is due mainly because of the higher ratio of ethanol in the blend and also due to the related agricultural activities. Thus, the influence of the choice of one of these functional units on the results is particularly important when the results of the LCA are meant to be used as a decision support tool.

According to our results, E10 and E85 fuel applications could reduce the dependence on fossil fuels (they should improve the security of energy supply) as well as a reduction in the GHG emissions regardless the selection of the functional unit. However, shifting from gasoline to ethanol should increase the emissions which contributes to PO, A and E in both cases. Ethanol fuelled vehicles release more NO_x, NMVOC, CO, NH_3 and N_2O in all their life cycle (Table 8).

LCA procedure helped identify the key areas in the *B. carinata* ethanol production life cycle where the researchers and technicians need to work to improve the environmental performance. Technological development could help in lowering both the environmental impact and the prices of the ethanol fuels.

5. Conclusions

This study focused on identifying the environmental impacts associated to the production and use of ethanol-based fuels (E10 and E85) taking into account two functional units based on mass of ethanol and driven distance. Although several impact categories have been analysed e.g. acidification, eutrophication, photochemical oxidants formation, global warming as well as fossil fuels extraction, further studies should be conducted on other types of impact in order to achieve a more complete scope of the impacts of fuel production such as toxicity categories and land use.

This paper tries to illustrate that the results of an LCA are strongly dependant on the chosen functional unit introducing always some type of uncertainty. E10 and E85 applications reduce the dependence on fossil fuels as well as the GHG emissions and increase the contributions to photochemical oxidants formation, acidification and eutrophication in spite of the selection of the

functional unit. E85 seems to be the best option in terms of global warming, fossil fuels extraction and photochemical oxidants formation. However, differences were predicted in terms of acidification and eutrophication depending on the functional unit chosen. Thus, E10 offers better environmental performance than E85 in both categories when a driven distance is considered as functional unit and the opposite result is achieved when mass of ethanol is assumed as functional unit. Therefore, the choice of the best blend (E10 or E85) from an environmental point of view depends greatly on the selection of the functional unit.

The use of other types of feedstocks such as forest residues as well as the culture of other kind of agricultural crops may imply less agricultural management than *B. carinata* biomass production. This should be clarified in further research. Further analysis should focus on different feedstocks for the second generation bioethanol production such as poplar biomass, hemp hurds, flax shives, wood etc.

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